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MEASURING σ_8 WITH CLUSTER LENSING: BIASES FROM UNRELAXED CLUSTERS

Graham P. Smith,[1,2] Alastair C. Edge,[1] Vincent R. Eke,[1] Robert C. Nichol,[3] Ian Smail,[1] and Jean-Paul Kneib[2,4]
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ABSTRACT

We use gravitational lens models and X-ray spectral analysis of 10 X-ray–luminous galaxy clusters at $z \simeq 0.2$ to study the impact of cluster substructure on attempts to normalize the matter power spectrum. We estimate that unrelaxed clusters are 30% hotter than relaxed clusters, causing σ_8 to be overestimated by 20% if the cluster selection function is not accounted for. This helps to explain the wide range in σ_8 derived from different techniques, $\sigma_8 \sim 0.6$–1, and offers a physically motivated explanation for some of the discrepancy. We identify two further systematics: (1) the extrapolation of small field-of-view mass measurements to cluster virial radii and (2) the projection of three-dimensional mass estimates from *n*-body simulations to match two-dimensional observables. We quantify these effects and estimate from the current data that $\sigma_8 = 0.75 \pm 0.05$(statistical) $\pm$ 0.15(systematic), where the systematic error reflects the extrapolation and projection uncertainties, and we assume $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. All three systematics (substructure, extrapolation, and projection) are fundamental to future cluster-based measurements of σ_8 regardless of the techniques employed. We identify gravitational lensing as the tool of choice for such studies because a combination of strong and weak lensing offers the most direct route to control the systematics and thus achieve an unbiased comparison between observation and theory.

Subject headings: cosmology: observations — gravitational lensing — large-scale structure of universe — X-rays: galaxies: clusters

1. INTRODUCTION

The spectrum of cosmic matter fluctuations is an important constraint on theoretical models of structure formation (e.g., Bond et al. 1991; Bower 1991; Lacey & Cole 1993). The amplitude of the power spectrum is parameterized as σ_8, the linear theory value of the rms fractional density fluctuations averaged in spheres of 8 h^{-1} Mpc radius at $z = 0$. Several methods have been used to estimate σ_8: the abundance of galaxy clusters (e.g., Eke, Cole, & Frenk 1996; Reiprich & Böhringer 2002; Viana, Nichol, & Liddle 2002), cosmic shear analyses (see van Waerbeke et al. 2002a for a recent review), and cosmic microwave background studies (e.g., Sievers et al. 2003; Bond et al. 2002). Current estimates of σ_8 range from ~0.6 to ~1.0, with statistical uncertainties in the range $\Delta\sigma_8 \sim 0.02$–0.15. The situation is characterized by disagreement between different methods and by the same methods applied to different samples. Systematic uncertainties probably lie at the heart of this disagreement.

In this Letter, we investigate systematic biases in the use of cluster abundances to measure σ_8. In principle, the mass function of galaxy clusters, $n(>M)$, should yield a direct constraint on σ_8. However, it is not currently possible to measure cluster masses with the precision and in the numbers required to construct a robust cluster mass function from direct measurement. The local cluster X-ray temperature function, $n(>T)$, has proved more accessible (e.g., Edge et al. 1990; Henry & Arnaud 1991; Ikebe et al. 2002). The X-ray temperature function in conjunction with a robust mass-temperature (hereafter M-T_X) calibration therefore offers an opportunity to constrain σ_8.

Observational attempts to calibrate the M-T_X relation typically rely on X-ray observations of clusters (e.g., Nevalainen, Markevitch, & Forman 2000; Allen, Schmidt, & Fabian 2001, hereafter ASF; Reiprich & Böhringer 2002). Despite the progress made by Allen (1998) in understanding X-ray–based cluster mass measurements, X-ray techniques are only well understood and therefore straightforward to apply to symmetric, equilibrium systems. This is a major concern because ~40%–70% of galaxy clusters appear to be dynamically immature (e.g., Mohr et al. 1995; Buote & Tsai 1996; Ota & Mitsuda 2002; Smith 2002, hereafter S02), and this immaturity has a measurable impact on the normalization of the cluster M-T_X and luminosity-temperature relations (Ota & Mitsuda 2002; S02; Randall, Sarazin, & Ricker 2002).

In contrast, mass estimates based on gravitational lensing are insensitive to the physical nature and state of the cluster mass. Lensing studies are therefore free from the symmetry and equilibrium assumptions that plague the X-ray studies. Attempts to use lensing to calibrate the cluster M-T_X relation have so far relied on previously published and/or crude cluster mass estimates (Hjorth, Oukbir, & van Kampen 1998; ASF; Viana et al. 2002). A major improvement on these pioneering studies would come from a precise and uniform analysis of a large, objectively selected cluster sample for which high-resolution space-based optical and X-ray data were available. In anticipation of such a program, we conduct a pilot study using S02's *Hubble Space Telescope* (*HST*)/*Chandra* gravitational lensing survey of 10 X-ray–luminous galaxy clusters at $z \simeq 0.2$. S02 made precise cluster mass and temperature measurements and thus constrained the high-mass end of the cluster M-T_X relation. They also studied the dependence of this normalization on cluster substructure, concluding that unrelaxed clusters are, on average, 30% hotter than relaxed clusters. S02's results therefore offer a unique opportunity to study the impact of cluster substructure on estimates of σ_8.

We summarize S02's results in § 2, describe our modeling and results in § 3, and summarize our conclusions in § 4. We express the Hubble parameter in terms of h, where $H_0 = 100\ h$ km s^{-1} Mpc^{-1}. We also adopt $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

[1] Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK.
[2] California Institute of Technology, MC 105-24, 1201 East California Boulevard, Pasadena, CA 91125; gps@astro.caltech.edu.
[3] Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213-3890.
[4] Observatoire Midi-Pyrénées, 14 Avenue Edouard Belin, F-31400 Toulouse, France.

2. *HST*/*CHANDRA* MASS-TEMPERATURE CALIBRATION

S02 studied a representative sample of 10 X-ray–luminous clusters ($L_X \geq 2 \times 10^{44}\ h^{-2}$ ergs s^{-1}, 0.1–2.4 keV) at $z = 0.21 \pm 0.04$, with line-of-sight reddening of $E(B-V) \leq 0.1$ from the XBACs sample (Ebeling et al. 1996). Each cluster was typically observed for three orbits (i.e., 7.5 ks) through the F702W filter using the Wide Field Planetary Camera 2 (WFPC2) on board *HST*. S02 used these data in conjunction with ground-based optical and near-infrared data (Smith et al. 2001, 2002) and the LENSTOOL software (Kneib et al. 1996; S02) to construct a detailed gravitational lens model of each cluster.

Armed with these models, S02 measured M_{2500}, the total projected cluster mass within r_{2500}, i.e., the radius at which the density of matter in the clusters falls to $\rho = \rho_{2500} = 2500\rho_c$, where ρ_c is the critical density required to close the universe.[5] S02 also divided the sample into relaxed ($M_{\rm sub}/M_{\rm tot} < 10\%$) and unrelaxed ($M_{\rm sub}/M_{\rm tot} > 10\%$) clusters, where $M_{\rm tot}$ is the total projected mass of the cluster within r_{2500} and $M_{\rm sub}$ is the projected mass of the cluster within the same radius that is not associated with the main centrally located dark matter halo. A complementary analysis of archival *Chandra* and *ASCA* observations of eight and one of these clusters, respectively, provided accurate measurements of the temperature of each cluster ($T_{\rm X,\,tot}$) within a projected radius of $r \leq 1\ h^{-1}$ Mpc. We refer the reader to S02 for further details of the modeling and analysis of these clusters.[6]

We plot S02's mass and temperature measurements in Figure 1. The open symbols show the individual clusters, and the filled symbols indicate the properties of the mean relaxed and unrelaxed cluster subsamples. The mean temperatures of the relaxed and unrelaxed clusters are $\langle T_{\rm X,\,tot}\rangle = 6.3 \pm 0.8$ keV and $\langle T_{\rm X,\,tot}\rangle = 9.2 \pm 1.2$ keV, respectively, where the error bars are bootstrap estimates of the uncertainties on the means. The unrelaxed clusters appear to be systematically 30% hotter than the relaxed clusters.

Two of S02's sample (A383: Smith et al. 2001; A1835: Schmidt, Allen, & Fabian 2001) have central cooling timescales of $t_{\rm cool} \lesssim 10^9$ yr. This is in line with expectations from other representative samples of X-ray–luminous clusters (e.g., Peres et al. 1998). S02 therefore recalculated all of the cluster temperatures using an $0.05\ h^{-1}$ Mpc $\leq r \leq 1\ h^{-1}$ Mpc annulus (i.e., excluding the cold core of the two extreme "cooling flow" systems). They found that while the temperature difference is slightly reduced ($\langle T_{\rm X,\,ann}\rangle_{\rm relaxed} = 6.9 \pm 0.9$ keV), it is robust to the exclusion of the central 50 h^{-1} kpc of each cluster from the temperature calculations. The 30% temperature difference therefore does reflect a bona fide difference between the ambient temperatures of relaxed and unrelaxed clusters.

3. MODELING AND RESULTS

3.1. *Approach*

We construct a simple model to investigate the impact of the intrinsic scatter in the cluster M-T_X relation identified by S02 on estimates of σ_8. We start with virial mass function of Jenkins et al. (2001) and fix $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and the power spectrum shape $\Gamma = 0.2$; i.e., we focus our attention solely on σ_8, which is a free parameter in the model. We convert this virial mass function to a mass function that matches the physical scales probed by S02's analysis, i.e., $r \leq r_{2500}$, assuming that the dark matter halos have concentrations given by the model of Eke, Navarro, & Steinmetz (2001). We then project this three-dimensional mass function onto a two-dimensional mass function using the calibration of Hjorth et al. (1998).

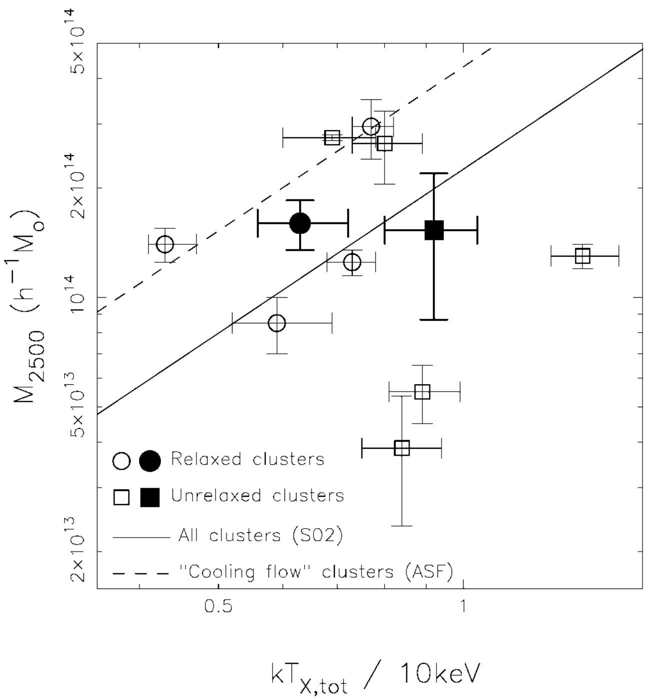

FIG. 1.—M_{2500}, the projected mass within r_{2500}, vs. the temperature of the intracluster medium for S02's sample of X-ray–luminous clusters. The open symbols show the individual clusters, and the filled symbols show the mean properties, of the relaxed (*circles*) and unrelaxed (*squares*) subsamples. The solid line shows (for $\alpha = \frac{2}{3}$) the M-T_X normalization of the entire S02 sample. The dashed line is a projected version (using the calibration of Hjorth et al. 1998) of ASF's cooling flow M-T_X relation. The ASF relation agrees with the two cooling flow clusters in S02's sample (A383 and A1835 are the two open circles that lie within 1 σ of the dashed line). The other two relaxed clusters that lie off the ASF line display weak evidence of possible past mergers.

To convert mass to temperature, we parameterize the cluster M-T_X relation: $T_{\rm X,\,tot} = AM^\alpha$, where $T_{\rm X,tot}$(keV) and $M_{2500}(10^{14}\ h^{-1}\ M_\odot)$ are defined in § 2 and A and α are the normalization and logarithmic slope, respectively. The small dynamic range (less than a decade in cluster mass; Fig. 1) and large intrinsic scatter of S02's sample precludes obtaining α from a fit to their data. Also, our goal is to investigate the impact of the normalization and scatter of the M-T_X relation on estimates of σ_8. We therefore fix α at the canonical value of $\frac{2}{3}$ (e.g., ASF). We also incorporate the uncertainty in the M-T_X normalization into the model using σ_T, defined as the scatter in log $T_{\rm X,\,tot}$ at fixed mass or, equivalently, the 1 σ uncertainty in log A. For any given M-T_X calibration, we therefore require two quantities from the observations (A and σ_T) to convert the projected mass function into a model temperature function.

We fit this model temperature function to the observed cumulative temperature function (Edge et al. 1990; Fig. 2). We estimate the 1 σ uncertainties on each data point in Figure 2 by bootstrap resampling with replacement. Although these data are cumulative and therefore correlated, the best-fit model (i.e., that which minimizes χ^2; see Eke et al. 1996 for more details) is insensitive to whether or not we formally incorporate the

[5] At $z = 0.2$, r_{2500} corresponds to the edge of the *HST*/WFPC2 field of view for the most massive clusters in S02's sample.

[6] This Ph.D. thesis is available upon request from gps@astro.caltech.edu.

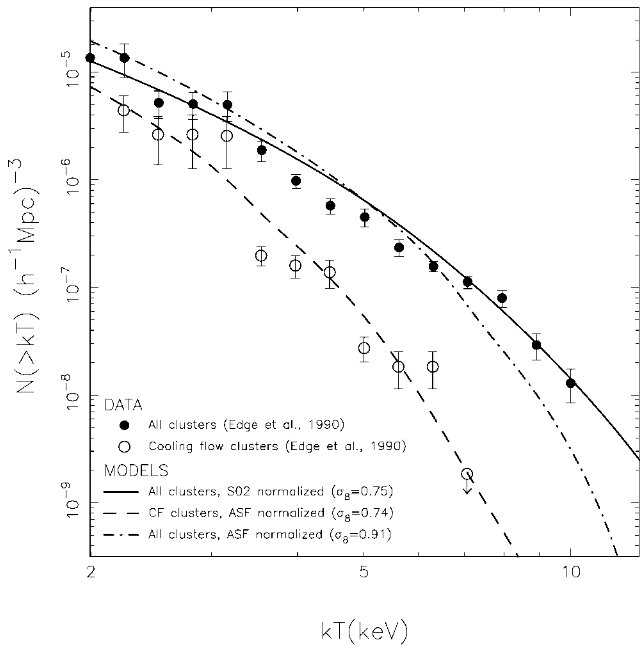

Fig. 2.—Edge et al. (1990) temperature function for all clusters and for cooling flow (CF) clusters (defined as containing a line-emitting central galaxy), together with the best-fit model temperature functions that are normalized with the S02 and ASF M-T_X calibrations. When a CF cluster–based normalization is applied to a representative sample of clusters, σ_8 is overestimated by ∼20% (compare the solid and dot-dashed curves). When the cluster selection function is accounted for properly in both the model normalization and the observed temperature function, consistent values of σ_8 are obtained (compare the solid and dashed curves).

covariance matrix into the fit. We therefore treat the data as uncorrelated. For given values of A and σ_T, this fitting procedure yields a best-fit value of σ_8.

3.2. *Model Fitting*

We use two independent M-T_X calibrations to normalize our models. We begin with S02's normalization and adopt the values of A and σ_T relevant to their entire sample: $A = 4.4$, $\sigma_T = 0.1$ (see the solid line in Fig. 1). This normalization yields a best fit of $\sigma_8 = 0.75 \pm 0.05$(statistical). We plot this best-fit model and the observed temperature function in Figure 2. Next, we turn to ASF's M-T_X relation. These authors observed a sample of seven cooling flow clusters with *Chandra*, and they used these data to normalize the M-T_X relation. We convert ASF's cooling flow M-T_X relation into the form required for our model: $A = 2.6$, $\sigma_T \simeq 0.03$. This normalization yields a best fit of $\sigma_8 = 0.91 \pm 0.07$(statistical). The ASF-normalized model (Fig. 2; *dot-dashed line*) fits the data less well than the S02-normalized model, with the largest residuals occurring at high temperatures.

The 20% offset in σ_8 between these two models appears to arise from a mismatch between the cluster selection function in ASF's work (i.e., cooling flow–only clusters) and the representative sample of X-ray–luminous clusters in Edge et al. (1990). We test this interpretation by fitting the ASF-based (i.e., cooling flow–normalized) model to an observed temperature function that describes only cooling flow clusters. We use the correlation between line emission from cluster central galaxies and short cooling timescales ($t_{\mathrm{cool}} \lesssim 10^9$ yr; e.g., Edge, Stewart, & Fabian 1992) to construct a "cooling flow–only" temperature function from the Edge et al. (1990) sample. We then fit the cooling flow model to the cooling flow data and obtain a best fit of $\sigma_8 = 0.74 \pm 0.05$(statistical), which agrees with the S02-based model. We plot this best-fit model and the relevant data in Figure 2. This model confirms that cluster substructure is an important and previously unidentified 20% systematic uncertainty.

3.3. *Extrapolation and Projection Systematics*

We investigate two further systematic uncertainties: the extrapolation of S02's *HST*/WFPC2-based lens models to the cluster virial radii and the projection of simulated dark matter halos in the Jenkins et al. (2001) mass function to two dimensions.

Our temperature function model (§ 3.1) extrapolates S02's lens models from r_{2500} to the cluster virial radii assuming that the clusters follow a Navarro, Frenk, & White (1997, hereafter NFW) profile at large radii; i.e., $\rho \propto r^{-3}$. S. Bardeau et al. (2003, in preparation) investigate this effect in detail through their weak-shear analysis of panoramic ($28' \times 42'$) CFH12k camera *B*-, *R*-, and *I*-band imaging of S02's cluster sample. Prior to the completion of this wide-field analysis, we note that weak-lensing analyses of individual clusters (e.g., King, Clowe, & Schneider 2002) are unable to discriminate between isothermal ($\rho \propto r^{-2}$) and NFW profiles on large scales. To quantify this systematic uncertainty, we integrate both profiles over the radial range $0.25\ h^{-1}$ Mpc $\lesssim r \lesssim 1.5\ h^{-1}$ Mpc (i.e., the dynamic range over which we are extrapolating). The uncertainty in profile shape introduces an uncertainty in virial mass estimates for an individual cluster of ∼30%, which translates into an uncertainty in cluster temperature (assuming $M \propto T_X^{3/2}$) of ∼20%. This equates to an uncertainty of ∼10% in σ_8. Assuming that the NFW profile adopted in our model is a steep limiting case, then this uncertainty would act to further reduce σ_8; we conservatively adopt ± 10%.

We also identify the projection of three-dimensional cluster masses from numerical simulations to observed two-dimensional masses (§ 3.1) as an important systematic uncertainty. As Hjorth et al. (1998) discuss, the magnitude of this uncertainty depends on the slope of the cluster density profile at small radii. Recent observational results (Smith et al. 2001; Sand, Treu, & Ellis 2002) indicate that there may be substantial intrinsic scatter in this slope, which appears to contradict theoretical claims for a universal profile (e.g., the NFW profile). Given these complications and the uncertainty as to whether the central slope is steeper or flatter than the NFW profile, we conservatively adopt a further ± 10% "projection" systematic uncertainty in σ_8. We note that if the slope is shallower than the NFW profile, then σ_8 would likely decrease and vice versa.

4. SUMMARY AND DISCUSSION

We have used S02's substructure-dependent cluster M-T_X normalization to investigate the impact of cluster substructure on estimates of σ_8. We find that when a cooling flow cluster M-T_X normalization is applied to the general cluster population, σ_8 is overestimated by 20%. A clear understanding of the cluster selection function is therefore vital to attempts to constrain σ_8 with cluster abundances. The simple X-ray luminosity selection of S02's sample (§ 2) enable us to account for this "substructure" systematic and thus to eliminate it from our analysis. We identify two further systematic effects that may bias our analysis: the extrapolation of S02's small field-of-view lens models out to the cluster virial radii and the uncertainties in the relationship between the three-dimensional mass information contained in numerical simulations and the two-dimensional mass information that is available from observations. We estimate conservatively that these effects combine to produce a further $\pm 20\%$ systematic uncertainty, and therefore we conclude from the present data that $\sigma_8 = 0.75 \pm 0.05$(statistical) $\pm$ 0.15(systematic). We also note that the recently reported discrepancies between *XMM*- and *Chandra*-based cluster temperature measurements (Schmidt et al. 2001; Majerowicz, Neumann, & Reiprich 2002; Markevitch 2002) may introduce further uncertainty into cluster abundance determinations of σ_8.

This 20% "substructure" systematic is similar to the discrepancy between the canonical value of $\sigma_8 \sim 0.9$–1 (e.g., Eke et al. 1996; Pierpaoli, Scott, & White 2001; Bacon et al. 2002; Bond et al. 2002; Hoekstra et al. 2002; Refregier, Rhodes, & Groth 2002; van Waerbeke et al. 2002b) and recent claims for $\sigma_8 \sim 0.6$–0.8 (Seljak 2002; Reiprich & Böhringer 2002; Borgani et al. 2001; Allen et al. 2002; Brown et al. 2003; Lahav et al. 2002; Schuecker et al. 2003; Viana et al. 2002; Jarvis et al. 2003). Our results therefore offer a physically motivated explanation for some of this discrepancy. Independent confirmation of this comes from the semianalytic study by Randall et al. (2002) of the effect of cluster mergers on the observed luminosity and temperature functions and thus on the inferred cluster mass function. Randall et al. predict that cluster mergers boost the observed temperature function and can cause σ_8 to be overestimated by 20% if hydrostatic equilibrium is assumed for nonequilibrium clusters, in agreement with our observational results.

All three systematics discussed in this Letter affect the ability of cluster abundance techniques to measure σ_8 accurately, regardless of whether gravitational lensing or X-ray techniques are used to measure the cluster masses. However, the insensitivity of gravitational lensing to the physical nature and state of the cluster matter means that a combined strong- and weak-lensing, space-based study of a large, objectively selected sample of clusters should be the tool of choice for future cluster abundance studies.

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